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ARTICLES

MICRO-SCALE LOOSE-BED PHYSICAL MODELS (GAINES/SMITH)

MICRO-SCALE LOOSE -BED PHYSICAL MODELS

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INTRODUCTION

Physical models are often used to investigate design and operational issues pertaining to complex hydraulic phenomena. These efforts employ scaled models to replicate fluid and transport processes in the prototype. The degree of sophistication for such models depends on the particular objectives of the investigation. Objectives range from determining detailed prototype flow conditions to evaluating general flow processes. Common subjects for modeling include: water movement and sediment transport in rivers and coastal zones; hydraulic performance of water-intakes, spillways, and outlets; flow around various objects; flow through or in conduits; flow-regulating devices; hydromachinery performance, floating structure or ship performance; and effluent-mixing processes (ASCE, 2000).

Physical models provide a means for evaluating costly prototype structures prior to construction. Such tests are justified by the relatively low cost of the model as compared to the potential cost of failure of the prototype structure. However, design, construction and operation of conventional large-scale models require lengthy timeframes and considerable costs. For this reason, recent trends have migrated away from physical model studies toward increased use of numerical modeling tools for analysis of all but the most complex prototype conditions, such as at pumping stations and for other hydromachinery applications. Attempts to use numerical models for "open river" problems have had mixed success. Small-scale physical models with movable bed materials that have attributes of a modest cost and quick turn around provide a potential economic means for continued use of physical models in solving river engineering problems (Davinroy, 1994, 1999).

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The use of loose-bed river models has enabled engineers to solve many complex riverine problems. Each application of a loose-bed river model requires the consideration of a variety of information. This information pertains to the following areas: (1) known prototype reach hydraulic conditions, (2) a definition of the reach problem, (3) the desired outcomes or alternative solutions, (4) model operational constraints, (5) the level of accuracy required for successful interpretation of model results, and (6) a basic understanding of river mechanics. These areas have a direct impact on successful model application.

Past utilization of small-scale models (and to a lesser extent, large-scale models) has given primary emphasis to areas (1), (2), and (3). Operational constraints (4) and basic river mechanics (6) have also been considered but in less tangible ways. For example, there are few documented model results that describe model design and operational considerations beyond a simplified description of procedures used in model calibration. Fewer still are reports that document prototype river mechanics and reach hydraulic characteristics and how those mechanics/characteristics were affected by model scales and distortions. The level of accuracy required for successful model operation (5) has received virtually no attention in previous work. Similarity relationships provide a means to investigate operational constraints (4), required accuracy (5), and basic river mechanics (6).

Similitude criteria attempt to establish a link between model and prototype where conditions in one can be used to successfully predict the value in the other. Achieving successful model results requires a degree of similarity between model and prototype conditions, yet flexibility in scale selection provides some freedom in model design and operation. The need for flexibility arises because models are generally too small to develop forces required to move typical model bed sediments. The additional forces needed to move the sediment at model scale must be provided by one or more of the following: increased discharge scales, exaggerated slopes, distorted vertical scale, reduced time scales, and/or modified bed sediment material properties. These distortions result in Froude and sediment-mobility similarity criteria that are in conflict. Instead of fulfilling stringent similarity requirements, most previous loose-bed model studies adopted an empirical approach to achieve model to prototype similarity. Empirical techniques attempt to reproduce the river-reach bed material movement and bed configuration with a reasonable sediment time scale.

Controversy regarding "correct" application of loose-bed models has persisted for many years. The small-scale models (micromodels) are no exception. One underlying issue that pertains to model acceptance involves the definition of what comprises an acceptable reproduction of prototype conditions. The work presented herein uses previous model study results to investigate this issue. Sixteen large-scale and 14 small-scale models are used. Gaines (2002) provides a listing of models included for this investigation.

The previous model study results were considered adequate for developing solutions to the particular problem under investigation. Therefore, these model studies help establish an acceptable standard for morphologic similarity requirements that can be associated with the types of problems and control measures investigated. These problems primarily consisted of channel control measures implemented by the

US Army Corps of Engineers. The present study also uses model and prototype data to evaluate similarity in sediment mobility for micromodels.

MORPHOLOGIC SIMILARITY

Vernon-Harcourt describes measures that demonstrate a successful model as: 1) the model reproduces the original existing conditions in the prototype, and 2) the model reproduces a future response of the prototype to a constructed training feature (Freeman, 1929). Application of this technique requires only that a model be verified against observed prototype response. Similarity criteria can be relaxed as necessary to achieve the necessary model response. Interpretation of model results is thus based on credibility gained through the verification and proving sequence more than reliance on similarity relationships. While past loose-bed modeling approaches utilized only the first part on Vernon-Harcourt's procedure, the verification concept describes the fundamental premise embodied in virtually all empirically based loose-bed modeling.

The micromodel technique does not utilize established hydraulic and sediment transport similitude criteria during design or operation of a model. Instead, micromodeling seeks a form of morphologic similarity (Davinroy, 1994) where overall bed configuration determines the degree of similarity between model and prototype. A number of previous investigators suggest using some type of morphologic similarity. Gaines (2002) provides a more complete discussion of the concept.

Micromodeling employs the first part of Vernon-Harcourt's procedure where the modeler interprets the degree of similarity between model and prototype bed configuration based upon their visual, qualitative comparison of model calibration runs. This approach for interpretation of similarity is consistent with methods used in large-scale modeling. No specific methodology is documented for prescribing the degree of morphologic similarity in either large-scale or micromodel studies. Study reports also lack any specific description of the assessment techniques used for determining model and prototype agreement for the calibration condition.

A consistent and quantitative method for assessing morphologic similarity is desirable. Parameters describing the channel morphology seem most useful for defining morphologic and hydraulic characteristics of the channel (Rosgen, 1994, and Leopold, et. al., 1964). Gaines (2002) describes a methodology for making quantitative comparisons of five hydraulic geometry parameters that define the model and prototype morphologic similarity. The five morphologic parameters are: thalweg location, cross-section area, water surface width, hydraulic depth, and the ratio of width divided by depth.

Analysis of individual bathymetric surfaces to obtain values for the five morphologic parameters began by considering individual Range values. Consideration of individual Range values revealed a high degree of variability through a model or prototype reach. Although expected, this variability caused difficulty in assessing similarity conditions for model application. Therefore, two approaches are required to ascertain the degree of model and prototype agreement. The first approach includes individual Range values in the calculation of model-to-prototype differences. The second approach involves the use of weighted reach values for the five morphologic parameters to explore similarity relationships for the previous model studies.

Relative frequency histograms or cumulative frequency (CF) graphs are used to analyze the large quantity of data that results from individual Range calculations. Selection of class intervals depends upon the range of measured data, the number of observations, and the behavior of the data. Haan (1977) discusses three methods for estimating the number of class intervals to use. Gaines (2002) utilized the following criteria in selecting the number of classes.

n = Number of Ranges	m=Number of class intervals
$17 \le n \le 23$	5
$24 \le n \le 46$	6
$47 \le n \le 93$	7

Cumulative frequency calculations for multiple surveys permit the quantification of differences between individual data sets. These differences can be expressed by comparing the areas bounded by each respective CF curve. For example, CF curves for thalweg position for the Kate-Aubrey 1:8000 micromodel are depicted in Figure 1. Estimates of reach mean values can be obtained for each morphologic parameter by estimating the value at a frequency level of 50 percent on the ordinate axis.

An expression of the model and prototype differences can be obtained by:

$$\mathrm{CFE} = \left(\frac{\text{Expected Model Value} - \text{Expected Prototype Value}}{\text{Expected Prototype Value}} \right) 100$$

where CFE is the cumulative frequency error expressed as a percentage and the expected model and expected prototype values are the parameter values determined for a frequency of 50 percent for the model and prototype, respectively. CFE values represent a quantitative measure of how well two CF curves agree. Smaller CFE values indicate better agreement while larger values indicate less agreement. However, the trends in the graph must also be used in interpreting the overall level of agreement.

Variability between model and prototype can also be expressed by the mean squared error calculated by the equation

$$\mathrm{MSE} = \frac{1}{n} \sum_{i=1}^{n} \left(\frac{\text{Model Value}_i - \text{Prototype Value}_i}{\text{Prototype Value}_i} \right)^2$$

where n is the number of Ranges under consideration, i is a counter, model value is the individual Range morphologic parameter value, and prototype value is the corresponding Range morphologic parameter value for the prototype. For reaches having multiple prototype bathymetric surveys, an average of all prototype surveys is used. Values of MSE should be compared with the CFE values and the CF graphs to assess model and prototype agreement.

Reach mean values estimated at the 50 percent frequency level on the CF curves may not fully represent reach characteristics and other methods of computing representative reach parameter values exist. To explore this possibility, two alternate methods for estimating reach mean values are considered. The two methods include the simple arithmetic averaging of Range values or the use of a reach weighting procedure. Gaines (2002) describes the weighting procedure used for the present study. Table 1 compares representative reach morphologic parameter values based upon the three methods.

Although there is some variation between values obtained by the three computational methods, the magnitude of variation is relatively small. Therefore, any of the three methods can be used to determine representative reach morphologic parameter values. However, assessing morphologic similarity requires a consideration of more than these values.

Assigning a level of morphologic similarity involves an integration of all five morphologic parameter values for the entire reach as well as within the specific problem area. The complex nature of this integration requires the use of three or more factors in evaluating morphologic similarity. These factors include: 1) an expression of the magnitude of error over the entire model reach (MSE), 2) a description of the relative position of model data relative to the prototype (CFE or similar difference calculation), and 3) a depiction of how the model relates to the prototype throughout the model reach (morphologic parameter values plotted by Range over the model length). CF graphs, morphologic parameter values versus Range plots, or model-prototype relationships depict the relationship between model and prototype over the of the reach. Morphologic parameters plotted by Range for the model length provide the simplest depiction of model and prototype agreement (Figure 2). Model-prototype relationships also visually portray the level of agreement (Figure 3).

Results from analyzing the thirty previous model study results indicate that MSE and difference values for the models are similar for both large-scale models and micromodels. Values for the area parameter are shown in Table 2. Other morphologic parameters exhibit similar results.

SEDIMENT TRANSPORT CHARACTERISTICS

The current micromodel technique does not utilize established hydraulic similitude criteria during the design or operation of a model. The micromodel procedure places significance on achieving morphologic similarity between model and prototype. The procedure also attempts to simulate the bed material movement by adjusting model operation (slope, sediment volume, or discharge) to obtain a desired level of sediment mobility. The relative state of mobility depends upon the modeler's judgement.

Consideration of sediment mobility as a model similarity requirement involves three distinct relationships: the point of incipient particle mobility, the general state of sediment mobility, and the particle's suspension characteristics. The

Shields curve (Shields, 1936, Buffington, 1999) represents the limiting condition between transport and no transport. This criterion requires two equations to describe sediment similitude. The particle Reynolds number (Re_*) and dimensionless shear stress (τ^*) can be calculated from the hydraulic and sediment characteristics of the given flow. Sediment similitude is satisfied if:

$$(\tau_*)_m=(\tau_*)_p \quad \text{and} \quad (Re_*)_m=(Re_*)_p$$

Garcia (2000) presents the Shields regime diagram (SRD) that can be used to differentiate between alluvial and gravel bed rivers. This form of the Shields diagram provides a simplified mechanism for the design and operation of loose-bed models. To facilitate a direct solution from the Shields diagram, Garcia uses a modified form of Re* that eliminates the occurrence of u* in both ordinate and abscissa. This form of the diagram is consistent with the approach suggested by Yalin (1992). Garcia substitutes the use of R_p for Re_* as

$$R_p = \frac{\left(\sqrt{\Delta g D}\right)D}{\nu} = \frac{Re_*}{\sqrt{\tau_*}}$$

where $\Delta = (\rho_s-\rho)/\rho$, ρ is the fluid density, ρ_s is the sediment density, D is a representative particle size, g is the gravitational constant, and ν is the fluid kinematic viscosity. The Shields regime diagram also aids in assessing the state of sediment suspension between model and prototype. The curve where $u_*=\omega$ defines a condition of similarity expressed by Zwamborn (1966) wherein the ratio of shear velocity to the fall velocity between model and prototype is unity. Garcia refers to the curve where $u_*=\omega$ for sand spheres as the transition between suspension and no-suspension of sediment particles on the Shields regime diagram.

Investigating the state of sediment mobility in the current investigation required establishing the point of incipient particle motion for the PlastiGrit sediments used in micromodeling. Fall velocity data helped define the suspension characteristics of the PlastiGrit sediment. Loose-bed flume experiments were used to determine the point of incipient particle mobility. Additional loose-bed flume experiments and two micromodel experiments provided data for computing τ_* values typical of micromodel conditions. The measured values are shown on the Shields regime diagram (Figure 4).

The τ_*, R_p data from the current investigation falls within the transitional zone as do most of alluvial sand-bed rivers at a state of bankfull discharge (Garcia, 2000). The Shields regime diagram in Figure 4 also shows Garcia's prototype data and large flume data as noted. The principle difference between Garcia's sand-bed river data and that of the present investigation was that the PlastiGrit data fell below the suspension curve defined by $u_*=\omega$. Because the PlastiGrit data fall below the no-suspension line, the suspension characteristics of prototype sediments is not faithfully reproduced. Therefore, the degree of suspension similarity is a limiting factor in micromodels.

Recent work by Lopez and Garcia (2001) presents a risk-based approach in assessing the incipient motion of particles. Lopez and Garcia suggest that the state of sediment suspension for $u_*=\omega$ results in a 17 percent probability that particles will become suspended. For $u_*=0.5\omega$ the probability is only two percent. The micromodel and small loose-bed flume data fall below the two-percent probability line for sand sediments. The curve $u_*=\omega$ for the PlastiGrit sediment plots near Lopez and Garcia's two-percent probability line for sand sediments. Therefore, the risk-based approach coupled with the position of the $u_*=\omega$ curve for PlastiGrit sediments supports that some relaxation of the suspension criterion is plausible.

In addition to the preceding sediment mobility characteristics, the investigation sought to evaluate similarity in sediment transport. Micromodeling employs an equilibrium sediment transport concept using sediment recirculation. The equilibrium concept implies the existence of a unique relationship between the physical characteristics of sediments, channel slope, discharge, flow depth, and boundary roughness. Determining model vertical scale as part of the calibration procedure acknowledges the relationship between flow depth and roughness and between sediment material and roughness. Sediment transport plays a significant role in each of these relationships.

Gaines (2002) presents a method that utilizes sediment transport to establish a relationship between roughness and slope distortions. Therefore, the present study attempted to measure sediment transport rates in small channels using a Micro-Motion® Coriolis mass density (CMD) meter. Figure 5 illustrates the CMD setup used in conjunction with the present study. The sediment recirculation employed in micromodeling and the limited volume of sediments contained within the small channels precludes using sediment extraction to measure the sediment transport rates. The principle interest in measuring sediment transport with an in-line meter stems from the need to maintain a consistent volume of sediment within the small experimental channels.

The CMD meter provides for continuous measurement of fluid density, volumetric flow rate, mass flow rate, and fluid temperature data. The CMD meter determines fluid parameter values by measuring the response of meter tubing as flow passes through the meter (Fisher-Rosemont, 1999). Because sediments typically used in micromodels are insoluble, the line density measured by the CMD reflects both water and sediment constituents. The non-linear methods presented by the Micro-Motion® user manual are used to determine the rate of solids (the sediment component) transport using a reference density for the fluid and the density of the solid material. Standard tables defining the physical properties of water provided the fluid reference density.

Problems encountered during analysis of the CMD data suggested that the meter was not capable of determining sediment transport rates for the experimental flume assembly. Investigations into the source of the problems led to a discovery that air entrainment caused the measured line density to be too low for the reference fluid density used. The free surface in the experimental channel permitted air to be entrained within the fluid. The CMD line density therefore represented a three component mixture - water, sediment, and air. Without a reference line density that reflected the air-water mixture, the data could not be used to determine sediment transport. For this reason, calculation of sediment transport for the study was not possible. Additional data collection for each experimental run would have permitted calculation of sediment transport rates. The additional data required for correct utilization of the CMD outputs are pre- and post-run fluid densities. Collection of the air/water fluid density before and after the experiment provides for adjustment of parameters used in converting line density to a solids transport rate over the course of an experimental run. Additional testing is necessary to confirm the validity of this procedure.

CONCLUSIONS

Successful model study results helps define an acceptable level of morphologic similarity between the model and prototype. Assessing morphologic similarity requires the consideration of three primary factors. Recommended factors are: 1) the reach MSE, 2) CFE or similar difference calculations, and 3) a depiction of how the model relates to the prototype throughout the model reach.

Similarity of sediment motion involves three distinct relationships: the point of incipient particle mobility, the general state of sediment mobility, and the particle's suspension characteristics. The Shields regime diagram provides a useful way to evaluate this criterion. Micromodel design should include an assessment of sediment mobility using the Shields regime diagram.

Implementation of micromodel or similar small-scale loose-bed modeling requires adaptive use of new techniques for measuring model variables of discharge, water level, and rate of sediment transport. The Coriolis mass density meter warrants further consideration as a means to determine sediment transport rates in small loose-bed models.

Table 1. Reach Morphologic Parameter Values - Kate Aubrey Reach, Mississippi River

Survey	Case	Method for Determining Reach Value	Number of Ranges	Area (sq. ft.)	Hydraulic Depth (ft.)	Width (ft.)	Width/ Depth	Thalweg Position
1:8,000 Micromodel	Model Calibration	Arithmetic	71	35540	15.6	2385	182	Na
		Reach Weighted		35993	15.2	2375	157	Na
		CF		35040	15.7	2376	184	3309
1973 Prototype	River	Arithmetic	71	45839	16.3	2983	209	Na
		Reach Weighted		45937	15.3	3010	197	Na
		CF		46136	16.3	2976	207	3227
1975 Prototype	River	Arithmetic	71	42688	18.4	2488	159	Na
		Reach Weighted		42333	16.6	2556	154	Na
		CF		42257	18.4	2470	159	3208
1976 Prototype	River	Arithmetic	71	46372	19.8	2509	148	Na
		Reach Weighted		46493	17.9	2603	146	Na
		CF		46102	19.7	2513	147	3195

Table 2. Area Comparisons for Thirty Previous Model Study Results

Large-Scale Model NAME	MODEL DIFF	MODEL MSE	Micromodel NAME	MODEL DIFF	MODEL MSE
Baleshed-Ajax	-0.406	0.213	Augusta	0.190	0.104
Blountstown	0.074	0.174	Clarendon	0.402	0.374
Buck Island	-0.248	0.149	Copeland	0.110	0.024
Chipola Cutoff	0.026	0.046	Kate-Aubrey 1:8000 Base	0.0685	0.216
Devil's Island	-0.048	0.063	Kate-Aubrey 1:8000 Predictive	-0.143	0.105
Dogtooth Bend	-0.011	0.179	Kate-Aubrey 1:16,000 Base	0.284	0.319
Kate-Aubrey 1:300	-0.218	0.331	Kate-Aubrey 1:16000 Predictive	0.111	0.184
Lake Dardanelle	0.058	0.248	Lock & Dam 24	0.128	0.063
Lock & Dam #2	-0.061	0.042	Memphis Harbor	-0.213	0.0911
Lock & Dam #4	0.257	0.156	Morgan City	0.040	0.048
Loosahatchie-Memphis	-0.003	0.023	New Madrid	-0.261	0.158
New Madrid Bar	-0.069	0.122	Salt Lake	0.205	0.0566
Redeye Crossing	-0.280	0.112	Savanna Bay	-0.171	0.0567
Smithland Lock & Dam	-0.098	0.073	Vicksburg	0.0221	0.114
West Access	0.037	0.014	White River	-0.351	0.156
Willamette River	0.028	0.028	Wolf Island	0.387	0.456

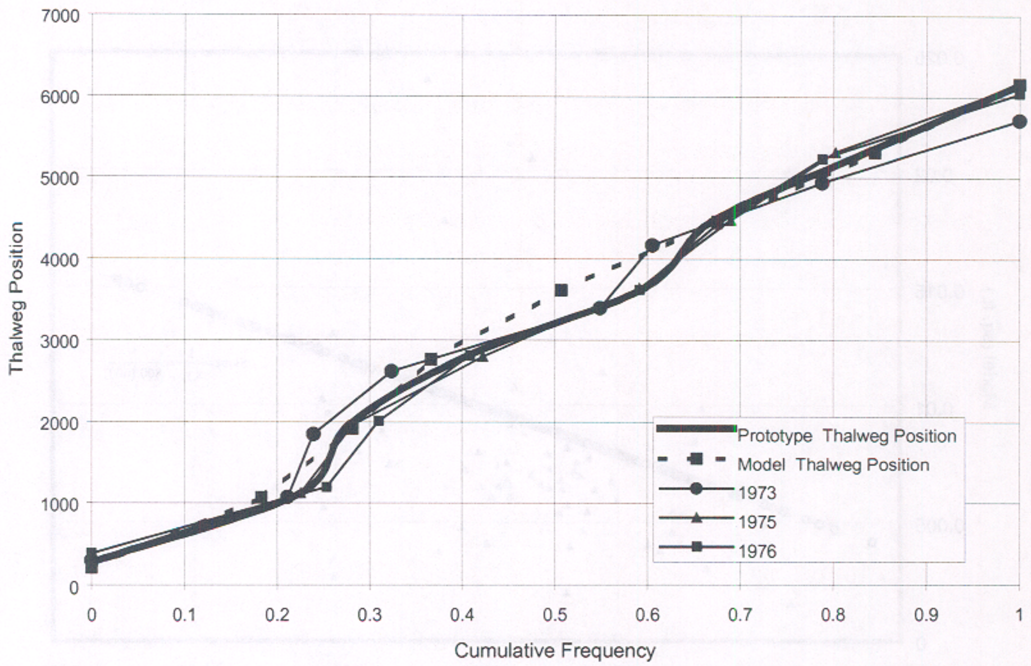

Figure 1. Cumulative Frequency Graph of Thalweg Position, Kate-Aubrey 1:8,000 Micromodel

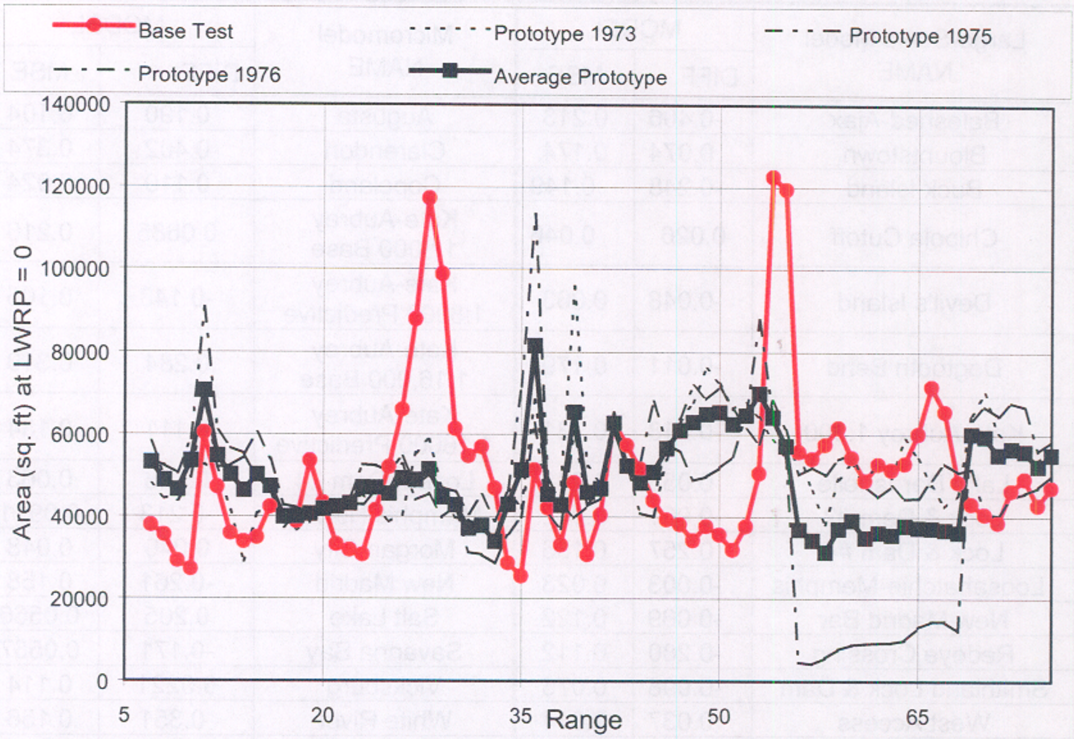

Figure 2. Morphologic Parameter Area versus Range, Kate-Aubrey 1:8,000 Micromodel

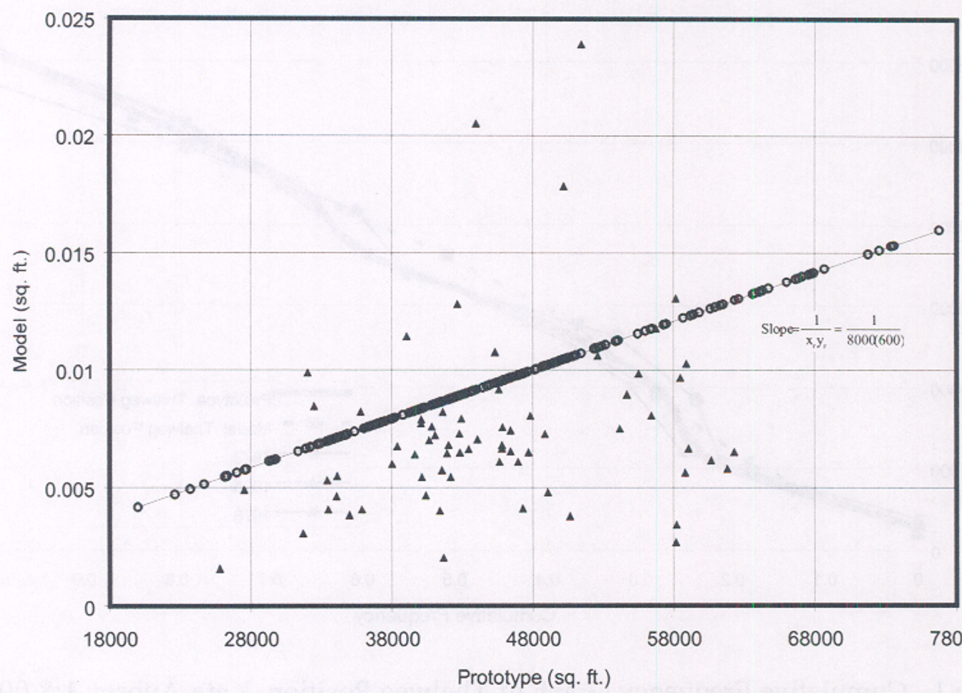

Figure 3. Model-Prototype Relationship for Area, Kate-Aubrey 1:8,000 Micromodel

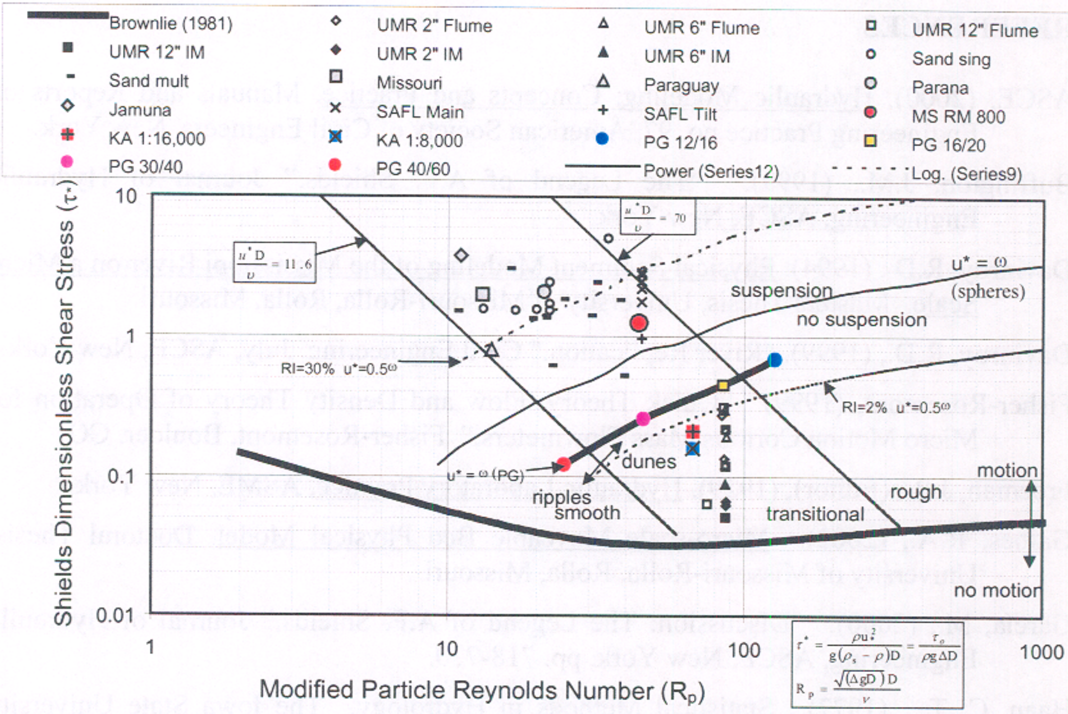

Figure 4. Shields Regime Diagram

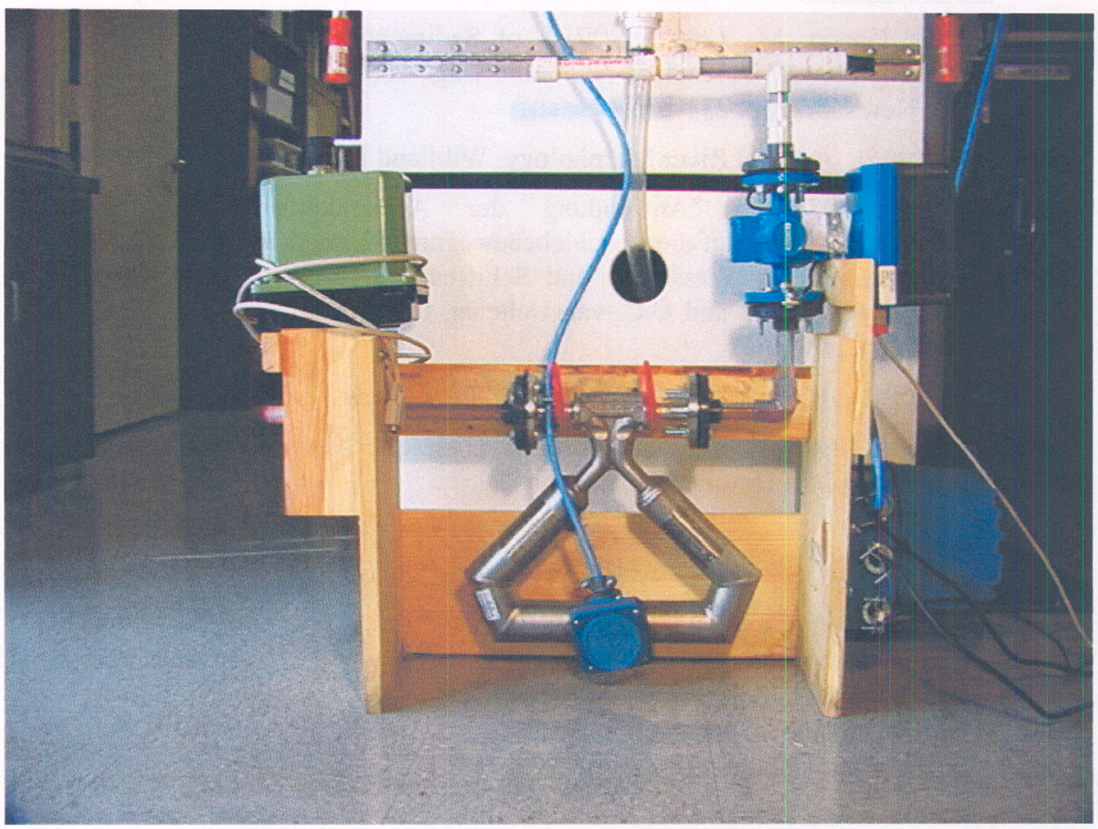

Figure 5. Coriolis Mass Density Meter Installation

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NOTATION

- D = Representative sediment particle size;
- Re_* = Particle Reynolds number;
- τ_* = Shields dimensionless shear stress;
- u^* = Shear velocity;
- ω = Particle fall velocity